Stream Krishna report 2003: The relative impact of climate variability and increasing water-use on the runoff of the Krishna River (India) during the past 100 years

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The relative impact of climate variability and increasing water-use on the runoff of the Krishna River (India) during the past 100 years

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Abstract

Studies show that both changes in climate variability and non-climatic factors such as water withdrawals may have profound effects on river runoff. There is, however, an increasing demand to study these effects at a regional to basin-scale since these effects will particularly affect water resources at this level. This paper attempts to differentiate between the effects of man-made hydrological developments and climate variability at a regional scale for the Krishna River Basin in India. The research shows the relation between climate variability and runoff using a statistical analysis. Furthermore, using calibrated and validated spatial hydrological model (STREAM), the runoff over the last 100 years is simulated under climate variability and increased water use for irrigation and hydropower generation. It appears that reservoir increase after 1960 cause a decrease in annual runoff of about 88 millimetres (42 %). Runoff under climate variability shows to vary only by about 44.3 millimetres (21.3 %). The study results and approach may enhance the discussion of the relative importance of climate change to regional hydrology of river basins.

1. Introduction

An important issue in studying the relation between climate and water resources availability is the relative impact of climate variability as opposed to effects of non-climatic factors, such as land-cover change, river training, reservoir construction and irrigation. Global change studies, such as described in the Third Assessment Report (TAR) of The Intergovernmental Panel on Climate Change (IPCC) state that increased climate variability due to climate change may severely impact water resources (Arnell et al. 2001), but do not indicate the dimension of these impacts as compared to other influences. Moreover, few studies have been conducted at regional or basin- scale, while most impacts from climate variability or non-climatic factors on water resources are expected at the basin and local scale.

Arnell et al. (1996: 330) list on the basis of published literature four anthropogenic non-climatic impacts on the water quality and water quantity; river impoundment and regulation, impact of land-use and land-use changes, water removal and effluent return and large scale river diversions. Also, quite some studies have been devoted to the quantification of the impact of climate variability on runoff (e.g. Arnell 2003). Very few studies however pay attention to the combined effect (e.g. Changnon and Demissie 1996), or the simultaneous monitoring of relative impacts of climate variability versus non-climatic factors. Peel et al. (2003) in their analysis of northern and southern hemisphere river basins show that not only precipitation but vegetation type may also determine the variability of discharges. Statistical analysis, such as by Arnell (2003) using climate change scenarios may show the impact of climate variability on runoff.

Water removal, in particular for irrigation, cause increased evapotranspiration and its effect on runoff can be quite substantial. Recent studies into the impoundment of water under various climatic settings have shown considerable effects on river runoffs, in particular on the reduction of peak flows with various consequences for downstream ecology and river morphology. For instance, Magilligan et al. (2003) estimate that the floods discharge that occurred every two years has decreased on average by about 60% for a number of river basins in the United States. Schreider et al. (2002) report that due to the construction of small farm dams in Australia small but detectable changes can be shown in daily discharges. Their research shows that calculating the residual between the modelled and observed flow can be used as a measure of the impact of dam development.

The main goal of this research is to perform regional analysis at the basin scale to quantify the relative impact of climate variability versus land-use change on runoff. We limit ourselves to study the impacts of the increasing water use for irrigation and hydropower on runoff over the last hundred years in the arid region of the Krishna River Basin in central India.

The objectives of this study are to:

- Perform a statistical analysis between the parameters of climate variability, in particular precipitation, and annual runoff.
- Calibrate and validate a spatial hydrological simulation model.
- Simulate monthly runoff over a 100-year period under climate variability.
- Estimate the changes in seasonal variability by calculating the residual between observed and modelled monthly discharges.

2. Study area and data

2.1 The Krishna River Basin

The Krishna River Basin is the second largest river in peninsular India and stretches over an area of 258,948 km^2. The basin represents almost 8 % of surface area of the state of India and was inhabited by 60.8 million people in 1991. Major tributaries include the Bhima River in the north and the Tungabhadra River in the south (Figure 2.1). The climate is characterised by sub-tropical conditions with considerable rainfall in the mountains of the Western Ghatts and arid conditions in the basin interior. The river terminates at the Krishna delta in the Bay of Bengal.

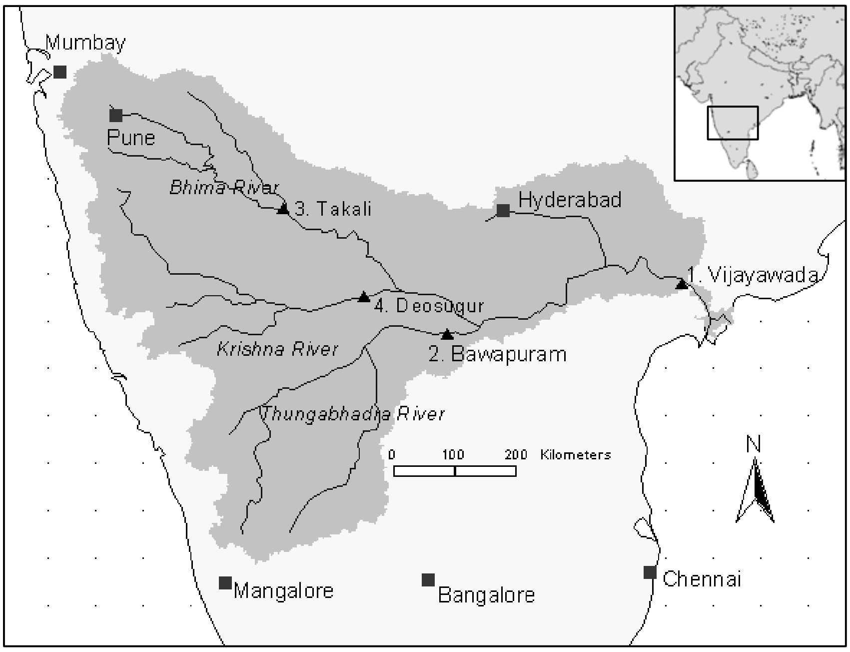


Figure 2.1 Map of the Krishna River Basin with major tributaries (in Italics), major cities around the basin and the discharge gauging stations used (numbered from 1 to 4).

Ever since human habitation of the area, tanks and small reservoirs have been constructed to conserve and utilise water. Major reservoirs and canal systems were constructed during the second part of the 19th century for irrigation purposes and later also hydropower generation. Since the independence of India in 1948 the construction of reservoirs started to take off. All large reservoirs with a live storage capacity of more than 1 million m^3 were built after 1953. The benefits of the water use are clear: the current area of land that is being irrigated amounts to about 3.2 million hectares and a total of 1,947 Mega Watts of electricity are being produced. In 1973 the water allocation between the three riparian states of Maharashtra, Karnataka and Andhra Pradesh was settled in water disputes act, but after the failing monsoons in 2001 and 2002 has caused considerable shortages in water and consequently increasing tension between the states.

The recent drought and the increasing use of water in the Krishna Basin have resulted in an absence of any runoff at the mouth during the last three monsoons in 2001, 2002 and 2003.

The rainfall over India is highly variable due to the intra-seasonal and inter-annual variability (Krishnamurthy and Shukla 2000). Potential and actual evapotranspiration in India have been decreasing and is expected to decrease further (Chattopadhyay and Hulme 1997), which is consistent with global observed trends that are being attributed to reduced radiation due to increasing cloud cover and aerosol concentrations (Roderick and Farquhar 2002), despite warming.

Future climate change as projected by IPCC using five global circulation models for the southern Asia region consists of a warming in the order of up to 3.5-4.2 degrees in winter and a warming of less than 2.5-3.0 degrees Celsius warming in summer. Precipitation in summer could slightly increase, by about 5-20%, while the simulation of change in winter precipitation is inconsistent between the models (Giorgi et al. 2001). Regional models however, show that on a smaller scale there may be distinct differences in precipitation change. Hassell and Jones (1999) use a regional nested model to simulate the southern Asian monsoon. In particular for the peninsular part of India the regional climate model predicts substantial decreases in precipitation under global warming.

2.2 Climate and runoff data

Climate data was retrieved from CRU TS 2.0 (Mitchell et al. 2003), covering the entire basin for the period 1901-2000. The average annual temperature for the earliest 30-year period was 26.0 degrees Celsius, while an average of 784.6 millimetres was recorded. A distinct decadal variability of both temperature and precipitation amount can be observed in the basin (Figure 2.2). Both parameters might have increased slightly. Temperature increased by about 0.6 degrees, from 26.0 between 1901-1930 to 26.6 degrees Centigrade over the period 1971-2000. Precipitation increased slightly over the same periods, from 784.6 to 817.6 millimetres.

It must be noted, however, that this climate data has not been corrected for ambient factors such as urban development or land use change and thus cannot be used to investigate actual climate change. For example, according to New et al. (2000) the CRU dataset is on average about 0.1 degree Centigrade warmer in the Northern Hemisphere than the corrected dataset that was used to investigate global temperature change by Jones (1994). However, the data set is the most comprehensive set available and it can be used for studying the effects of climate variability on runoff.

Data on average, maximum and minimum observed monthly river discharges were taken from the GRDC database (Fekete et al. 2000) and the RivDIS database (Vörösmarty et al. 1998) for four gauging stations at the main river and the three tributaries depicted in Figure 2.1. The main station close to the mouth of the river (number 1, Vijayawada) covers the period 1901-1979, with no data during the period 1961-1964 and in 1975.

Station numbers 2 and 3 (Bawapuram and Takali) only contain data for the period 1968-1979, while station number 4 (Deosugur) only has data for 1971-1979, the year 1975 is missing at all three stations.

Observed discharge data was converted from cubic metre per second into runoff in millimetres using the (sub-) basin sizes reported by Fekete et al. (2000), and is shown in Figure 3.2

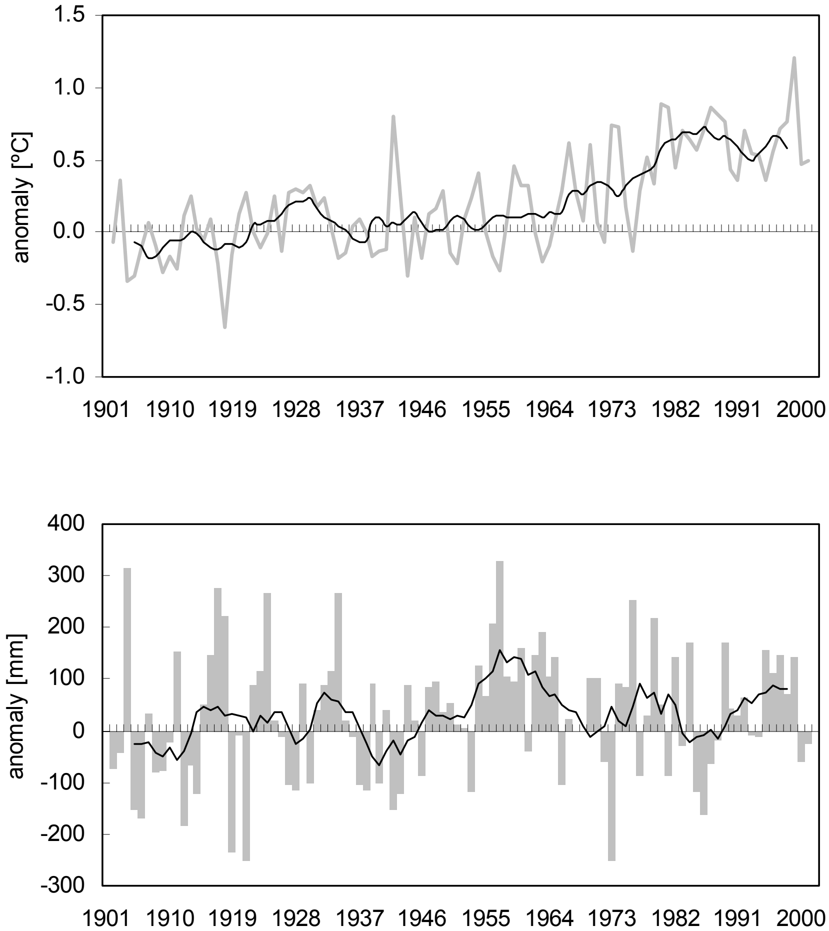


Figure 2.2 Temperature (a) and precipitation (b) anomalies in the Krishna River Basin relative to the period 1901-1930 (data from Mitchell et al. 2003).

3. Estimating changes in annual runoff

The climate data, discharge data and data on reservoir construction are investigated in order to detect relationships between water use and (downstream) discharge changes. The effect of the increasing use of water for irrigation and hydropower generation is estimated from a simple statistical relationship between total annual precipitation and runoff.

The increase in storage capacity of reservoirs larger than 10^6 m^3 can be clearly seen from Figure 3.1 The entire basin has currently a live storage capacity of over 34.5 x 10^9 m^3, the majority of which (about 33 x 10^9 m^3) is present in reservoirs larger than 10 x 10^6 m^3, the remaining 1.5 x 10^9 is present in numerous smaller tanks and barrages spread out over the area. Perhaps the most important impact of dams on river runoff is the damping of peak flows and the height of the annual peak flow has significantly decreased in the most recent period (Figure 3.1). There appears to be a threshold storage capacity at which the peak runoff declined, from about 1966 onward, the moment when the seven-year moving average drops below the long-term minimum.

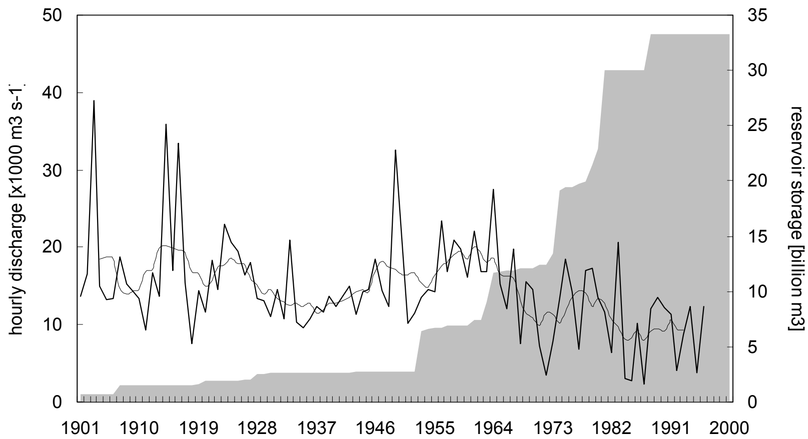


Figure 3.1 Maximum discharge over the period 1901-1996 at station number 1 Vijayawada (line), its seven year moving average and cumulative live reservoir storage capacity over the period 1901-2000 (shaded area) (discharge data from Rodier and Roche 1984, updated to 1996).

When the total annual runoff in millimetres is expressed as a percentage of precipitation it can be shown that during the period 1901-1960 on average 27.3 % of total annual precipitation is discharged at the mouth of the river into the Bay of Bengal (Figure 3.2). When comparing the decades 1901-1930 and 1931-1960 the percentage of runoff remains fairly constant, at 26.8 and 27.7. % respectively, despite a 5.3 % increase in precipitation over the same periods. During the period 1965-1979 (excluding 1975), however, only 14.8 % of total annual precipitation is reaching the lower end of the basin.

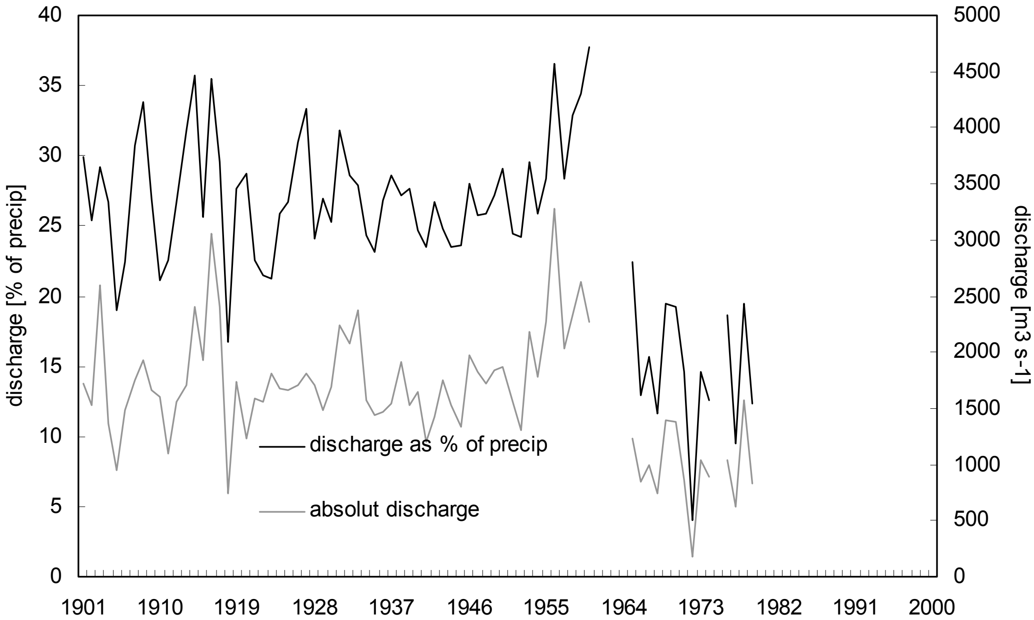


Figure 3.2 Total annual runoff and total annual runoff as percentage of precipitation at station number 1 (Vijayawada).

Correlation between the total annual runoff and total annual precipitation shows that there is a fairly constant relationship between both parameters, with a correlation coefficient of $r^2 = 0.63$ (Figure 3.3). The period 1965-1979 (excluding 1975) shows a different relationship because of the increasing use of water for irrigation. Also, some years in the 1970s were relatively dry (Figure 2.2), adding to the reduced outflow.

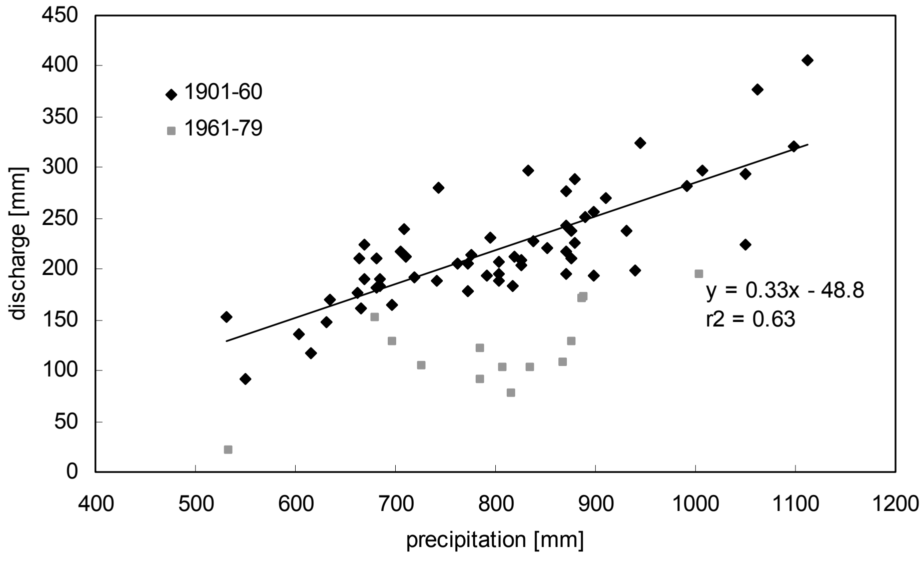


Figure 3.3 Relationship between total annual precipitation and total annual runoff for the periods 1901-1960 and 1965-1979 (excluding 1975) at station number 1 (Vijayawada).

The correlation function between the runoff and precipitation can be used to give an estimate of the annual runoff. In Figure 3.4 the actual and estimated total annual runoff are depicted. The variation in runoff over the period 1901-1960 area quite accurately described by this correlation function.

Next, the root mean square error c over the estimated runoff values and the observed runoff values was calculated using the equation

$$c = \sqrt{\frac{1}{n}\sum (x_{a,i} - x_{b,i})^2} \qquad (3.1)$$

,where $x_{a,i}$ is the estimated value using equation 1 in Figure 3.3, $x_{b,i}$ is the observed value at the same time step i and n is the number of observations. The root mean square error of the estimated runoff is 34.1 millimetres over the period 1901-1960.

Figure 3.4 shows that the expected runoff figures in the period after 1965 are much higher than the observed runoff figures. When combining this discrepancy with the reservoir development depicted in Figure 3.3, it appears that increased storage capacity is indeed the main cause of decreased downstream annual discharge.

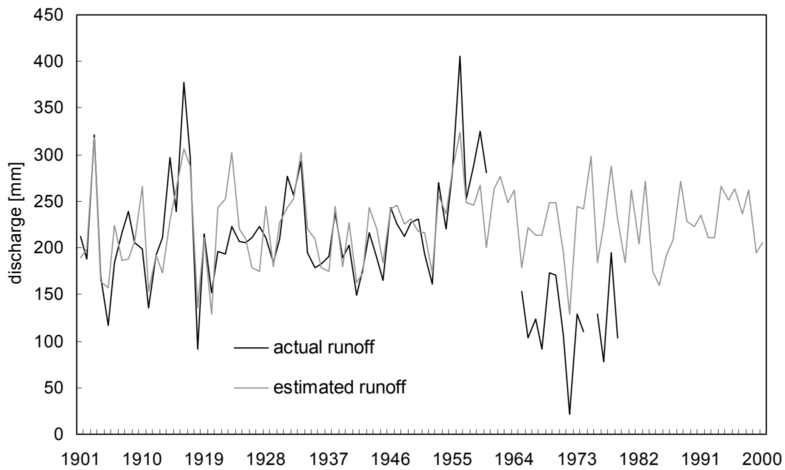


Figure 3.4 Expected runoff for period 1901-2000 based on correlated precipitation and runoff observations over the period 1901-1960 at station number 1 (Vijayawada).

4. Estimating changes in monthly runoff

The general idea of using a hydrological simulation model is that the discharge data by itself shows indeed a change in runoff, but this is not normalised for the decadal fluctuations in precipitation as seen in Figure 2.1, thus obscuring the influence of different environmental factors. Incorporating only the precipitation of a particular month into the statistical relationship as show in Figure 3.3 ignores the fact that runoff is also influenced by the precipitation of the preceding period, as well as by other factors such as evapotranspiration/temperature. By using a hydrological model the basic hydrological processes including variation of climatic parameters, storage and delayed runoff of water and evapotranspiration allows to make a more quantitative distinction between the runoff that would be expected and the actual record that contains both the environmental changes that are of interest; climate and reservoir development.

4.1 Hydrological modelling

A spatial water balance model called STREAM is used to assess seasonal changes in the hydrological cycle. The model calculates river runoff, water availability and aridity on the basis of temperature and precipitation inputs, using the relatively simple Thornthwaite method for the calculation of the potential evapotranspiration. This approach has been successfully applied to climate and water studies in other river basins with similar size and characteristics as the Krishna basin (Van Deursen and Kwadijk 1994; Aerts et al. 1999; Aerts et al. 2000; Middelkoop 2001). The STREAM model uses GIS (geographical information system) data for the Krishna River at a spatial resolution of 3 x 3 km and uses a monthly time step. The spatial resolution is sufficient to analyse large-scale patterns, considering the basin size. Also, similar studies confirm that the monthly time step that is being used is sufficient for the detection of decadal, inter-annual and seasonal changes in the hydrological cycle that are caused by long-term processes such as storage change and climatic variability.

4.2 Calibration and validation

First, the model was calibrated and validated. We assume a baseline period between 1901 and 1930, because during this time relatively little reservoir capacity was constructed (Figure 3.1) and thus a more or less natural hydrological situation existed. The STREAM model was first calibrated for the period 1901-1915 using first a factor that influences the amount of evapotranspiration, so that the average annual amount of runoff calculated at station number 1 (Vijayawada) was identical to the average annual observed amount for the period 1901-1915. Next, the separation coefficient between directs runoff and 'slow flow' from groundwater storage was determined by matching the observed seasonal runoff cycle. This calibrated model was finally applied to the period 1916-1930 for validation. The monthly runoff figures calculated by the model for both periods, 1901-1915 and 1916-1930, are shown in Figure 4.1.

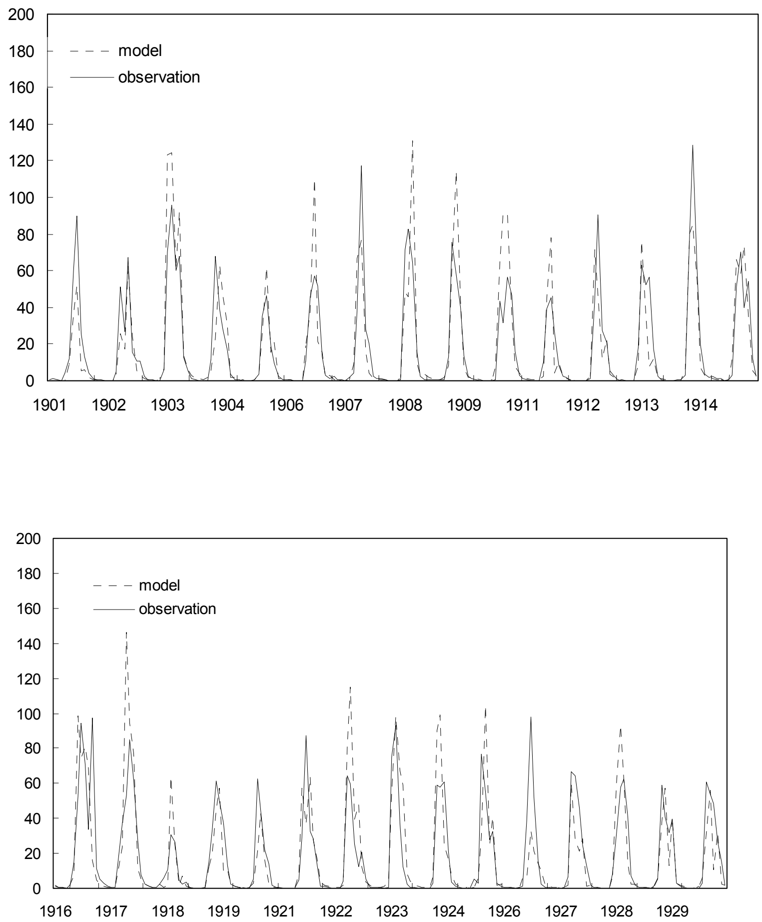


Figure 4.1 Comparison of modelled and observed runoff (mm) for the calibration period 1901-1915 (a) and validation period 1916-1930 (b).

Furthermore, the performance of the model was tested using a regression coefficient and a model efficiency coefficient. The model efficiency coefficient R^2 from Nash and Sutcliffe (1970) is calculated using the equation

$$R^2 = \frac{F_0^{\,2} - F^2}{F_0^{\,2}} \tag{4.1}$$

The initial variance $F_0^{\,2}$ in Equation 2 is calculated using

$$F_0^{\,2} = \sum (q_i - \overline{q})^2 \tag{4.2}$$

,where $\overline{q}$ is the mean observed runoff and q_i the observed runoff at time step i.

The index of disagreement is calculated using

$$F^2 = \sum (q_i' - q_i)^2 \qquad (4.3)$$

,where q_i' is the modelled runoff value and q_i is the observed runoff value at time step i.

Table 4.1 Observed and modelled mean total annual runoff, correlation coefficients (r^2*) and model efficiency coefficients (*R^2*) for the main gauging station for the calibration period (1901-1915) and the validation period (1916-1930) and the four subsequent 15-year periods. Note that the number of compared months is indicated by* **n**.

Period	n		Runoff [mm] Observed	Modelled	r^2	R^2
1901-1915	180	Calibration	208.5	208.5	0.71	0.64
1916-1930	180	Validation	213.2	210.4	0.59	0.47
1931-1945	180		206.7	206.3	0.74	0.66
1946-1960	180		254.6	252.9	0.75	0.66
1961-1975	120		118.0	212.7	0.55	-0.73
1976-1990	48		126.3	197.8	0.75	0.20

The coefficients for the calibration (1901-1915) and the validation (1916-1930) periods are given in Table 4.1. The regression coefficient r^2 of 0.71 indicates that the model performs quite well for the calibration period. The r^2 coefficient is smaller (0.59) for the validation period. The R^2 value for the validation period (0.47) is much smaller than the value for the calibration period (0.64), but the calculated regression coefficient gives us enough support to assume that the model is able to simulate the broad seasonal patterns. During the two subsequent 15-year periods (1931-1945 and 1946-1960) the model appears to be performing even better than during the calibration and validation periods (see Table 4.1). This could be either due to the fact that the CRU climate data accuracy is improving after 1930, or because of the reduced variability of precipitation (see Figure 2.2), which may lead to inaccurate estimations of the hydrological model in the period 1901-1930.

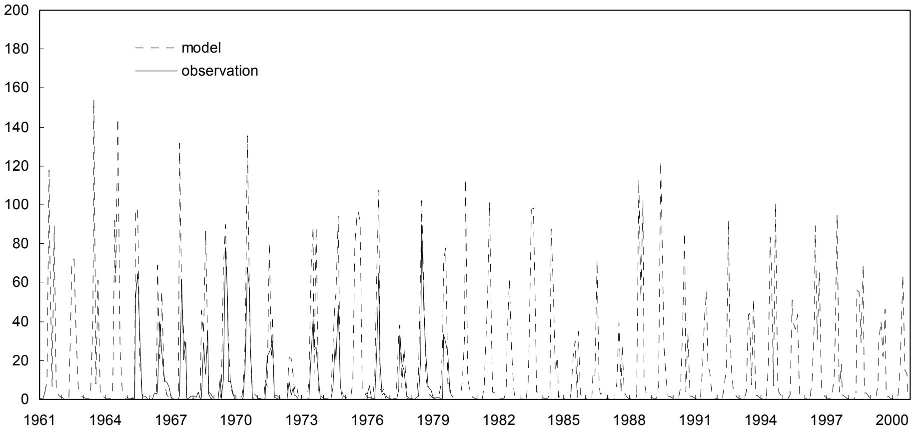
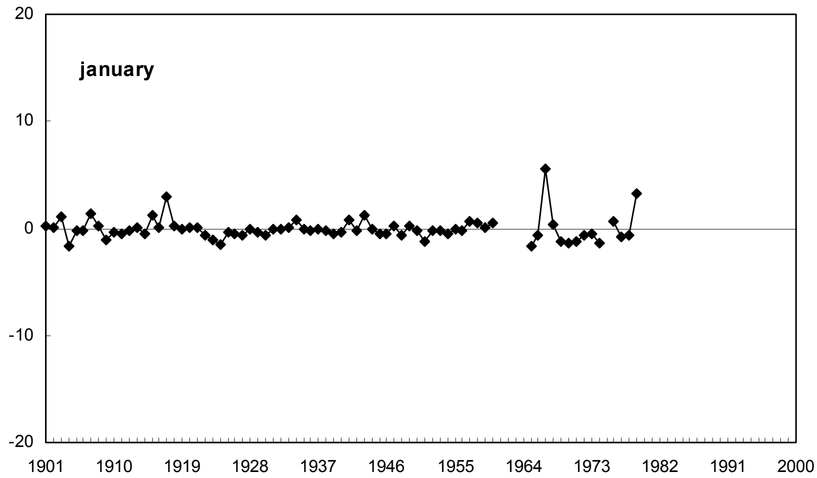
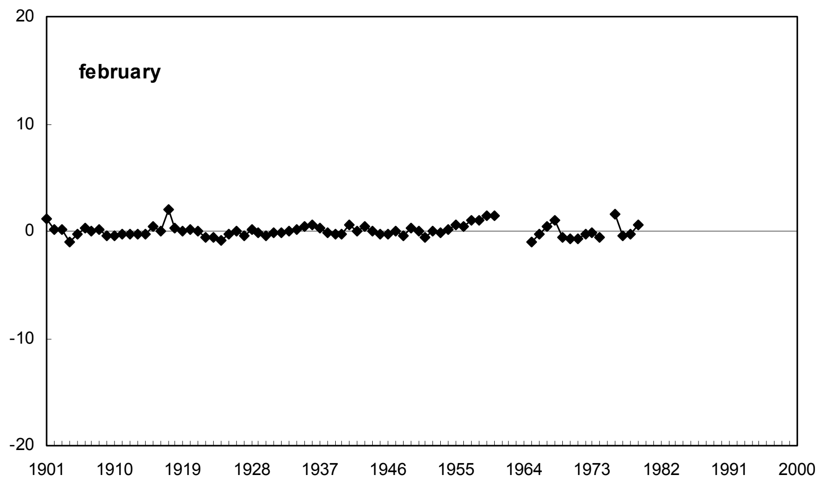


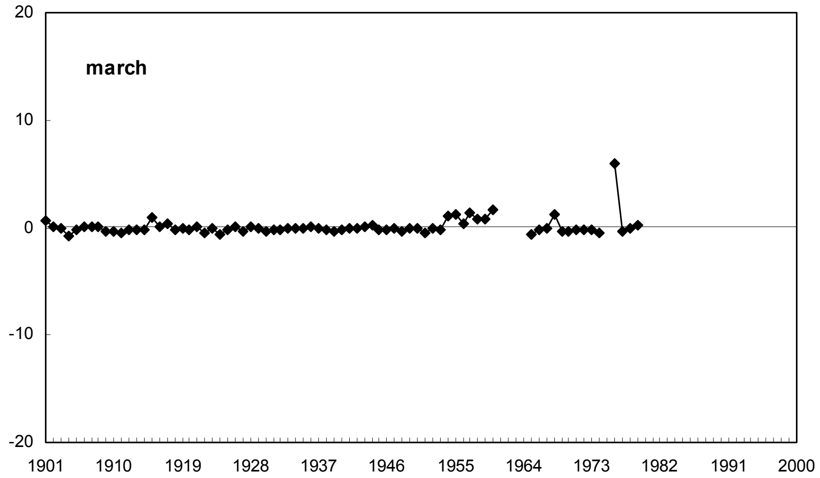
Figure 4.2 Observed and modelled runoff for the period 1961-2000.

5. Discussion

After the calibration and validation the hydrological model was used to calculate runoff for the period 1961-2000, the period that shows a relatively large increase in reservoir development. The model was run using the parameters that were found during the calibration and validation exercise. From Figure 5.1 it becomes clear that the average runoff has decreased considerable, since the model simulates much higher runoff based on precipitation and no changes in reservoir capacity.



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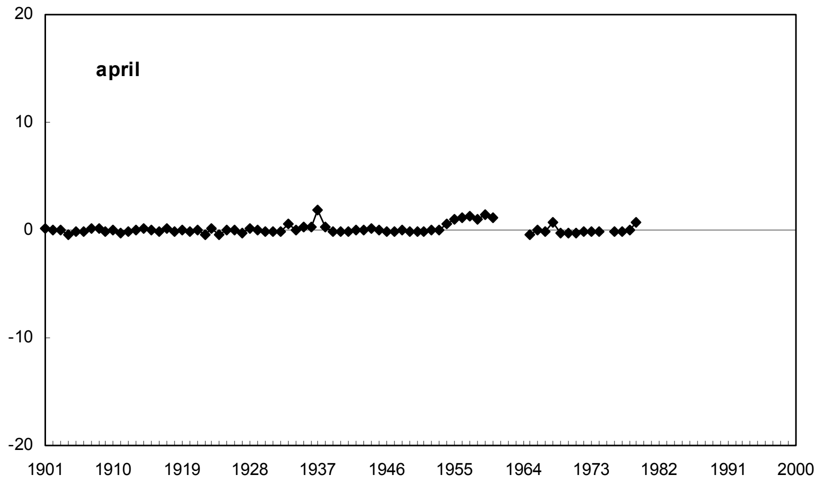
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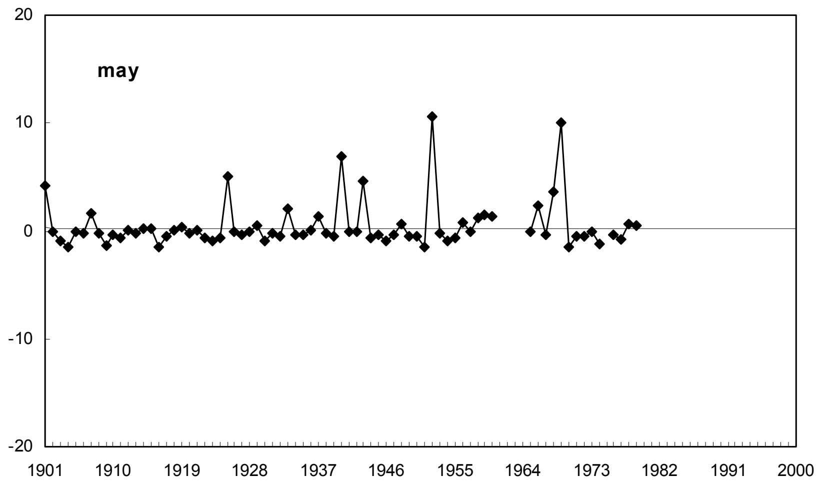
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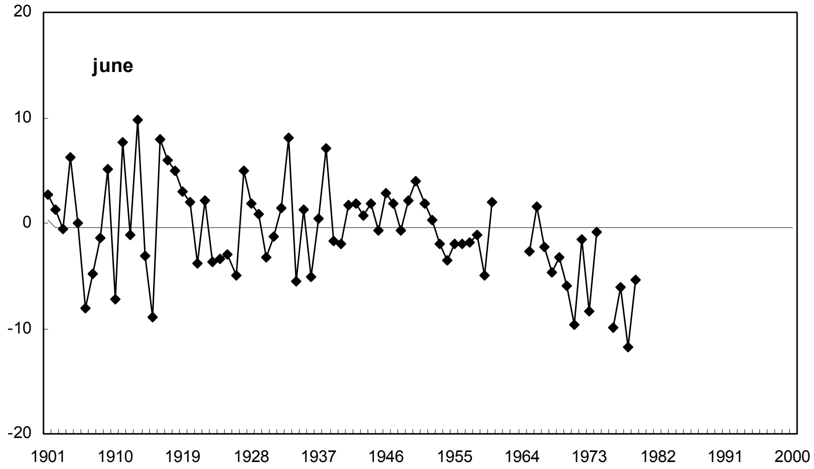
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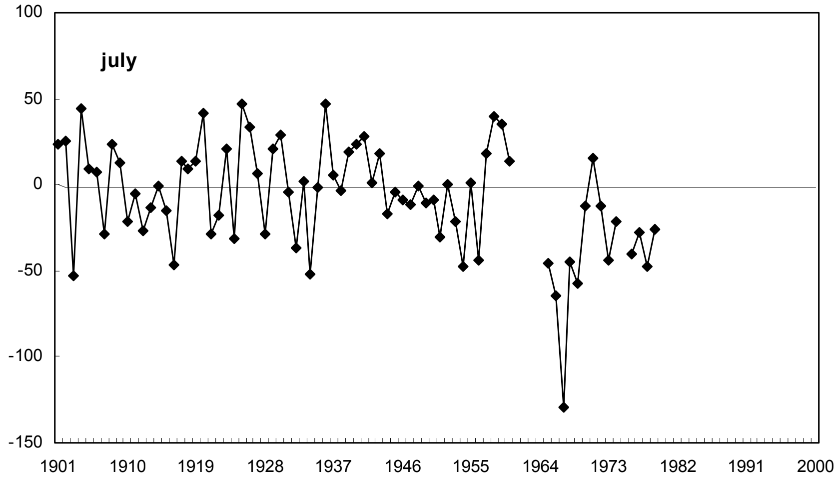
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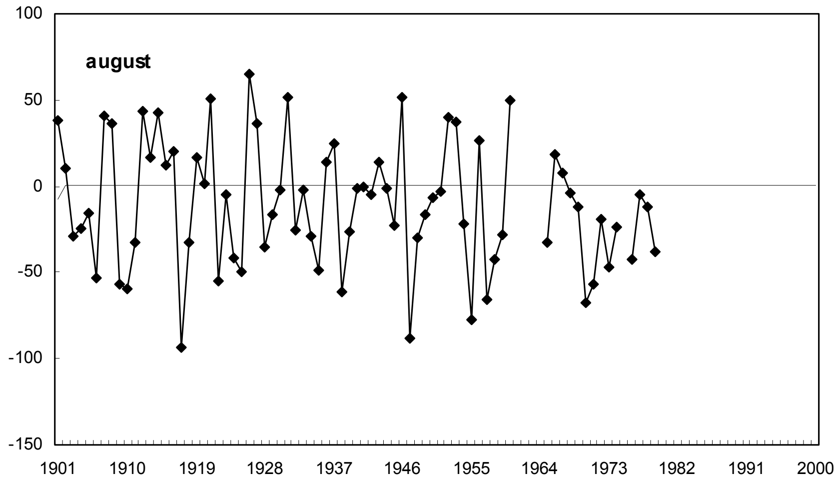
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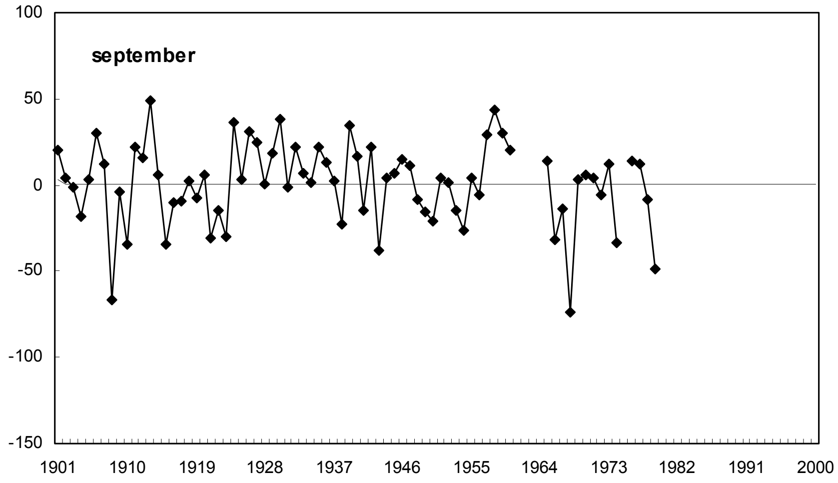

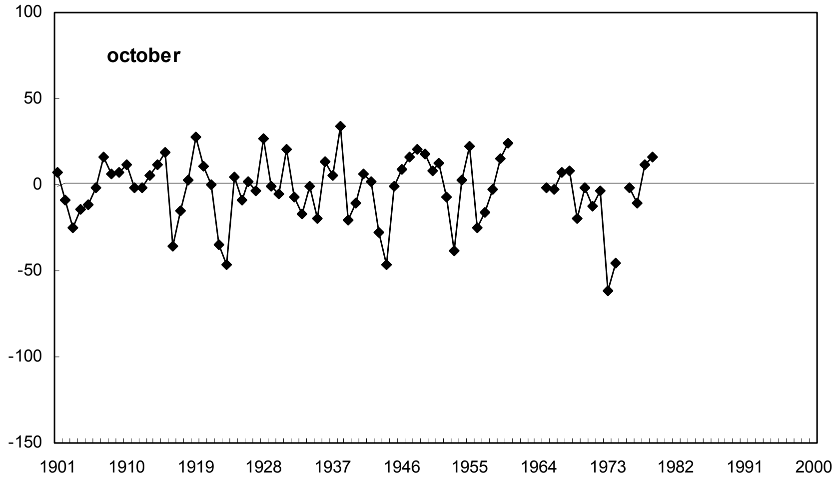

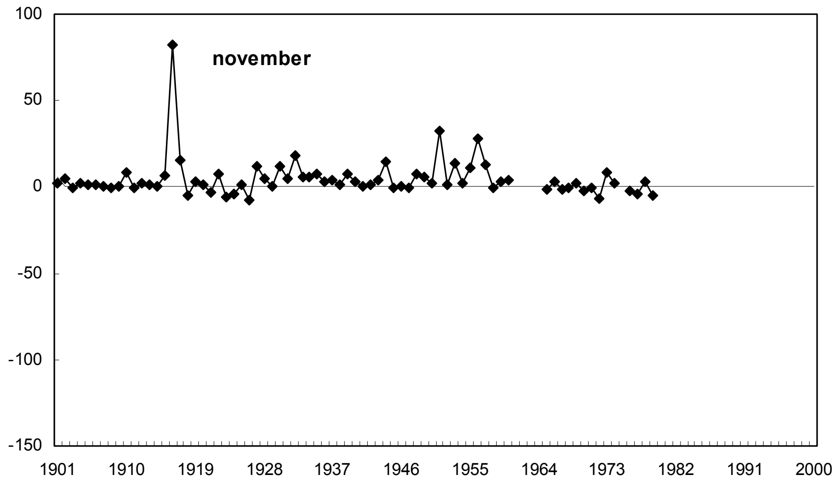

Figure 5.1 Differences (mm) between observed and simulated monthly runoff 1901-1979.

More detail on changes in monthly runoff is given in Figure 5.2, where the residual (difference between the simulated and observed runoff) over the period 1901-1979 is plotted against time. The difference between the simulated and observed runoff is a measure of environmental impacts other than climate variability (in particular precipitation), since this is included in both the observed and modelled runoff. We believe that this difference is mainly caused by the impediment of the river channel by increasingly more reservoirs, in particular because the changes in the residual as seen in Figure 5.2 coincide with the increase in reservoir construction as seen in Figure 3.1.

During the dry season no great differences are found. In the months February, March and April an increase can bee seen as compared to the same period in the 1950s, caused by an increase in total annual precipitation (see Figure 2.2). In the early stage of the monsoon season, the largest differences between the model and the observations are found, in particular in the months of June, July and August. Smaller differences are found the later in the season, during the months September, October and November.

Table 5.1 Average and standard deviation of the residual runoff in the dry period and monsoon period during the time intervals of 1901-1960 and 1961-1979.

Season	Period	Runoff [mm]	
		Average	Standard deviation
Dry season	1901-1960	6.3	13.5
	1961-1979	-0.1	6.9
Monsoon	1901-1960	-5.1	56.7
	1961-1979	-88.0	33.4

Seasonal changes are depicted in Figure 5.2. The average and standard deviation values of the residuals are given in Table 5.1. In the dry season, little changes can be observed, although a slight increase since about the 1940s appears to be present (Figure 5.3), perhaps because more water is released out of the reservoirs during this period. Afterwards, there is a slight decrease in both the average and the standard deviation in the dry season. During the monsoon period, the average amount of water that is extracted from the river increased from a negligible amount in the period 1901-1960 to approximately 88 millimetre on average (Table 5.1).

This amount is about 42 % of total average runoff that would have been available in the period 1961-1979. When we compare this decline of 88 millimetres with the standard deviation of total annual runoff, which is 44.3 millimetres during the period 1961-1979, it becomes clear that the structural decline in runoff due to the dam construction is about twice as large as declines from the impact due to the year to year climatic variability

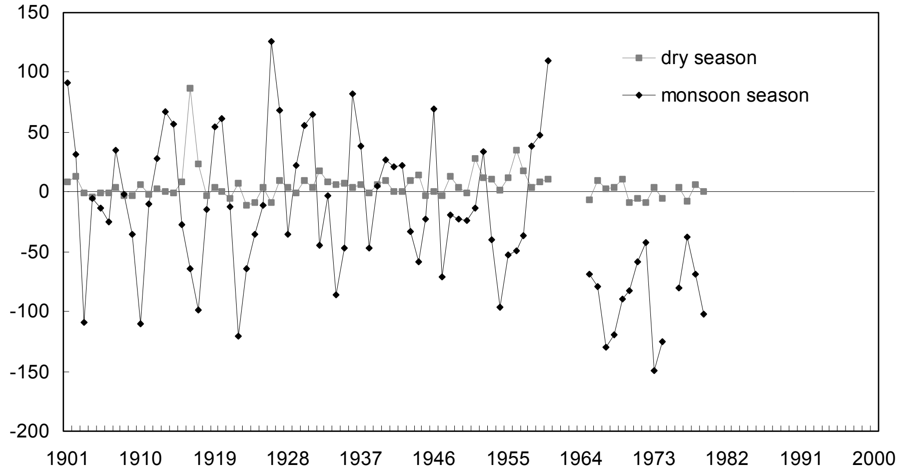

Figure 5.2 Difference (mm) between simulated and observed runoff during the dry season and monsoon periods 1901-1979.

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6. Conclusions

The statistical analysis has shown that the period after 1960 appears to deviate the period before 1960 in terms of the runoff per amount of precipitation. Our hydraulic model is able to quite accurately simulate the runoff of the Krishna River Basin over a period of 100 years. The runoff as estimated by the model deviates from the observed discharges, in particular during the period after 1960. An analysis of the residual shows that a structural amount of approximately 88 millimetres (or 42 %) can be attributed to factors other than climate variability. Observed climate variability accounts for a variation of approximately 44.3 millimetres during the period 1961-1979.

These results imply that when analysing the impact of climate variability and climate change, other variable and structural environmental changes can be as important. Future studies may need to take other changes, such as deforestation and changes in evapotranspiration that were only roughly estimated in this study, into account. Further study in this particular case and location will have to focus on the analysis of the period after 1979 up to 2000.

Acknowledgements

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